A Performance Evaluation of Open Source Erasure Codes for Storage Applications

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A code $\mathcal{C}$ over $\mathbb{F}_q$ is $\mathbb{F}_q$-linear if $\mathcal{C}$ is a vector space over $\mathbb{F}_q$...
My Perspective on Storage

Open Source Libraries

Here's your starting point!

Storage System
Programmers
The Point of This Talk

To inform you of the current state of open-source erasure code libraries.

To compare how various codes and implementations perform.

To understand some of the implications of various design decisions.

When you go home, you can converse about erasure codes with your friends & families.
Erasure Coding Basics/Nomenclature

You start with $n$ disks:
Partition them into $k$ data and $m$ coding disks.

Call it what you want: 
“$k$ of $n$.”
“$k$ and $m$,”
“$[k,m]$.”

But please use $k$, $m$, and $n$. 
You *encode* by calculating the $m$ coding disks from the data.
You *decode* by recalculating lost data from the survivors.

An “MDS” code will tolerate any $m$ failures.
Disks are composed of **blocks**, stripes, and strips.
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Reed-Solomon Codes

Strips are $w$-bit words, where $n \leq 2^w$.

When $w = 8$, strips equal bytes.
Reed-Solomon Codes

Coding is described by a matrix-vector product.

Generator Matrix $G^T$.

Arithmetic is special and expensive.

This is all that matters.

Data $m$ * 

Stripe $k$

"Codeword"
Bit Matrix Codes

Strips are each $w$ individual bits. Arithmetic is binary: Addition = XOR, Multiplication = AND

Generator Matrix $G^T$. 

Stripe = “Codeword”
Bit Matrix Codes

Thus, coding bits are XOR sums of various data bits:

\[ \text{Stripe} = \text{Codeword} \]

\[ G^T \]

\[ k \]

\[ m \]

\[ mw \]

\[ \text{Generator Matrix} \]

\[ \text{Data} \]

\[ \text{XOR} \]

\[ \text{Stripe} = \text{“Codeword”} \]

Performance is clearly proportional to the number of ones in the Generator Matrix.
Bit Matrix Codes

For good performance, strips are composed of \textit{packets} rather than bits.

\begin{align*}
kw & \text{ Generator Matrix } G^T. \\
& \{ \text{ Data Packets } \} \times \{ \text{ XOR } \} \Rightarrow \{ \text{ Codeword Packets } \}
\end{align*}
Bit Matrix Codes

Cauchy Reed Solomon (CRS) Codes [Blomer95]

- Bit Matrix derived from Reed-Solomon code.
- Same constraints: All good as long as $n \leq 2^w$.
- [Plank&Xu06]: Optimization to reduce ones.
- Further optimization [Plank07].
The Special Case of RAID-6

- Two coding disks: \( P \) & \( Q \).

- \( P \) drive is parity (superset of RAID-4/RAID-5).

- Last row (or last \( w \) rows) of Generator Matrix all that matter.
The Special Case of RAID-6

Reed-Solomon Coding Optimization [Anvin07]:

- Multiplication by two can be implemented faster than general multiplication in $GF(2^w)$.

- Arrange the Q row to take advantage of this.

\[
\begin{array}{cccc}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 \\
\end{array}
\]

Improves encoding but not decoding.
Optimized Cauchy Reed-Solomon Codes [Plank07]:

- For all $w$, enumerate best values for the $Q$ row.

- Different $w$ have different properties based on the underlying Galois Field arithmetic.

E.g: $k = 14$: Average ones per row:

- $w = 7$: 22.3
- $w = 8$: 28.5
- $w = 9$: 20.1
The Special Case of RAID-6

Minimal Density RAID-6 Codes ($k \leq w$):

- Provably minimal number of ones.
  - $(w+1)$ is prime: Blaum-Roth codes [1999]
  - $w$ is prime: Liberation codes [Plank08]
  - $w = 8$: Liber8tion code [Plank08]

- Performance improves when $w$ increases.

- Requires a scheduling technique [Hafner05] for good decoding.
The Special Case of RAID-6

**EVENODD [Blaum94] & RDP [Corbett04]:**

- \((w+1)\) prime, \(k \leq w\).
- Scheduled non-minimal bit matrices.
- Perform better when \(w\) is smaller.
- When \(w = k\) or \(k+1\), RDP is provably optimal.
- Patented.
Open Source Libraries

- **Luby**: Original CRS code.
  - (1990 – C)
- **Zfec**: Reed-Solomon coding, $w = 8$.
  - (2007 - C, based on Rizzo 1997)
- **Jerasure**: All of the codes described above.
  - (2007 – C)
- **Cleversafe**: CRS from cleversafe.org, $w = 8$.
  - (2008 – Java, based on Luby)
- **RDP/EVENODD**: Added to Jerasure.
Open Source Tests - Encoding

1. Read

2. Encode

3. Write

Big File

Data Buffer

Block $D_0$
Block $D_1$
Block $D_2$
...
Block $D_{k-1}$

Coding Buffer

Block $C_0$
...
Block $C_{m-1}$

Disk

File $D_0$
File $D_1$
File $D_2$
...
File $D_{k-1}$
...
File $C_0$
...
File $C_{m-1}$
Open Source Tests - Encoding

Block $D_0$
- $DS_{0,0}$
- $DS_{0,1}$
- ...
- $DS_{0,s-1}$

Block $D_1$
- $DS_{1,0}$
- $DS_{1,1}$
- ...
- $DS_{1,s-1}$

Block $D_{k-1}$
- $DS_{k-1,0}$
- $DS_{k-1,1}$
- ...
- $DS_{k-1,s-1}$

Data Buffer

Encoding Stripe 0

Block $C_0$
- $CS_{0,0}$
- $CS_{0,1}$
- ...
- $CS_{0,s-1}$

Block $C_{m-1}$
- $CS_{m-1,0}$
- $CS_{m-1,1}$
- ...
- $CS_{m-1,s-1}$

Coding Buffer
Open Source Tests - Encoding

Data Buffer

Block $D_0$

$DS_{0,0}$

$DS_{0,1}$

$\ldots$

$DS_{0,s-1}$

$\ldots$

$DS_{k-1,0}$

$DS_{k-1,1}$

$\ldots$

$DS_{k-1,s-1}$

Block $D_1$

Block $D_{k-1}$

Block $C_0$

$CS_{0,0}$

$CS_{0,1}$

$\ldots$

$CS_{0,s-1}$

$\ldots$

$CS_{m-1,0}$

$CS_{m-1,1}$

$\ldots$

$CS_{m-1,s-1}$

Coding Buffer

Encoding Stripe 1
Open Source Tests - Encoding

Data Buffer

Block $D_0$
- $DS_{0,0}$
- $DS_{0,1}$
- ...
- $DS_{0,s-1}$

Block $D_1$
- $DS_{1,0}$
- $DS_{1,1}$
- ...
- $DS_{1,s-1}$

Block $D_{k-1}$
- $DS_{k-1,0}$
- $DS_{k-1,1}$
- ...
- $DS_{k-1,s-1}$

Encoding Stripe $s-1$

Coding Buffer

Block $C_0$
- $CS_{0,0}$
- $CS_{0,1}$
- ...
- $CS_{0,s-1}$

Block $C_{m-1}$
- $CS_{m-1,0}$
- $CS_{m-1,1}$
- ...
- $CS_{m-1,s-1}$
Blowing up further.

Block $D_0$

Each strip is of size $wp$.

Each block is of size $swp$.

Data buffer is of size $kswp$.

$w$ packets each of size $p$. 
Parameter Space Explored

- 1GB Video File, ~100 MB data buffer.
- Four configurations: [6,2][14,2][12,4][10,6]
- All implemented codes.
- All legal values of $w \leq 32$. 
Machines

- **#1: MacBook (32-bit)**
  - 2 GHz Intel Core Duo (only one used).
  - 1 GB RAM, 32KB L1 Cache, 2MB L2 Cache.
  - `memcpy()`: 6.13 GB/s, XOR: 2.43 GB/s.

- **#2: Dell (32-bit)**
  - 1.5 GHz Intel Pentium 4.
  - 1 GB RAM, 8KB L1 Cache, 256KB L2 Cache.
  - `memcpy()`: 2.92 GB/s, XOR: 1.53 GB/s.
The Measurements that You'll See

- Strip out the disk I/O.
  - You are only seeing encoding/decoding times.

- Averages of 10+ runs, 0.5% variance.

- Show raw speed and “normalized.”
Cache Effects: The packet size.

RDP - [6,2]. $w = 6$ on MacBook.

This is not a nice smooth curve with a clear maximum.
Encoding Performance: [6,2]
Observation #1
Special purpose codes rock.

Observation #2
XOR count roughly matters.

But so does the cache.
Observation #3. While RDP is a clear winner, others are very close behind.
**Observation #4.** In Cauchy Reed-Solomon Coding, the matrix makes a big difference, as does $w$. 
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\[ w = 8 \]
\[ w = 16 \]
\[ w = 32 \]
Observation #5. Anvin's optimization is a winner for Reed-Solomon Coding. Zfec has the best performance of the standard Reed-Solomon encoders.
Encoding Performance: \([14, 2]\)
Encoding Performance: [12,4]
Observation #1: The matrix matters still. [12,4]
Observation #2: Smaller $w$ are better.
Decoding Performance: [6,2]
Conclusions from the study

- Open source erasure code implementations can easily keep up with disks, even on slow CPUs.
- Special purpose RAID-6 codes are much better than general-purpose alternatives.
- Cauchy Reed-Solomon coding is the better general purpose code.
- With Cauchy Reed-Solomon coding, the matrix matters.
- With all codes, attention must be paid to $w$ and to memory/cache.

**Biggest impact of further research:** Beat Reed-Solomon coding beyond RAID-6.
Anticipating Some Questions:

“Your machines suck.”

“Why didn't you use better ones?”

“Why no multicore?”

“Why no use of SSE?”

HP DC7600, Pentium D820, 64-Bit, 2.8 GHz.
Anticipating Some Questions:

“My friend has an implementation of Reed-Solomon that blows all of your codes away.”

“What do you have to say about that?”

Cool. Post it.

“Why didn't you test the Reed-Solomon codec in the Linux kernel?”

My bad. We should have.
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Cache Effects: The packet size.

RDP - [6,2]. \( w = 6 \) on MacBook.

**Observation #1**
This is not a nice smooth curve with a clear maximum.
Cache Effects: The packet size.

RDP - [6,2]. \( w = 6 \) on MacBook.

Observation #2
Adjacent values can differ radically.

P = 3268, Speed = 1266
P = 3272, Speed = 997
Result

A heuristic search algorithm to find the “best” packet size.

Remaining graphs always show performance of the best packet size.